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[54] **METHOD FOR IN SITU CLEANING OF ELECTRON EMITTERS IN A FIELD EMISSION DEVICE**

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[57] **ABSTRACT**

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[52] U.S. Cl. **445/59**

[58] Field of Search 445/59, 9, 10, 445/16; 313/309, 336, 351, 495

A method for in situ cleaning of electron emitters (126, 226, 326, 526) in a field emission device (100, 200, 300, 400, 500) includes the steps of controllably providing hydrogen gas (142, 242, 342, 542) within the field emission device (100, 200, 300, 400, 500) at a time during the operational life of the field emission device (100, 200, 300, 400, 500) and, thereafter, emitting electrons from the electron emitters (126, 226, 326, 526), thereby forming hydrogen free radicals, which decontaminate and condition the emissive surfaces of the electron emitters (126, 226, 326, 526).

[56] **References Cited**

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21 Claims, 3 Drawing Sheets

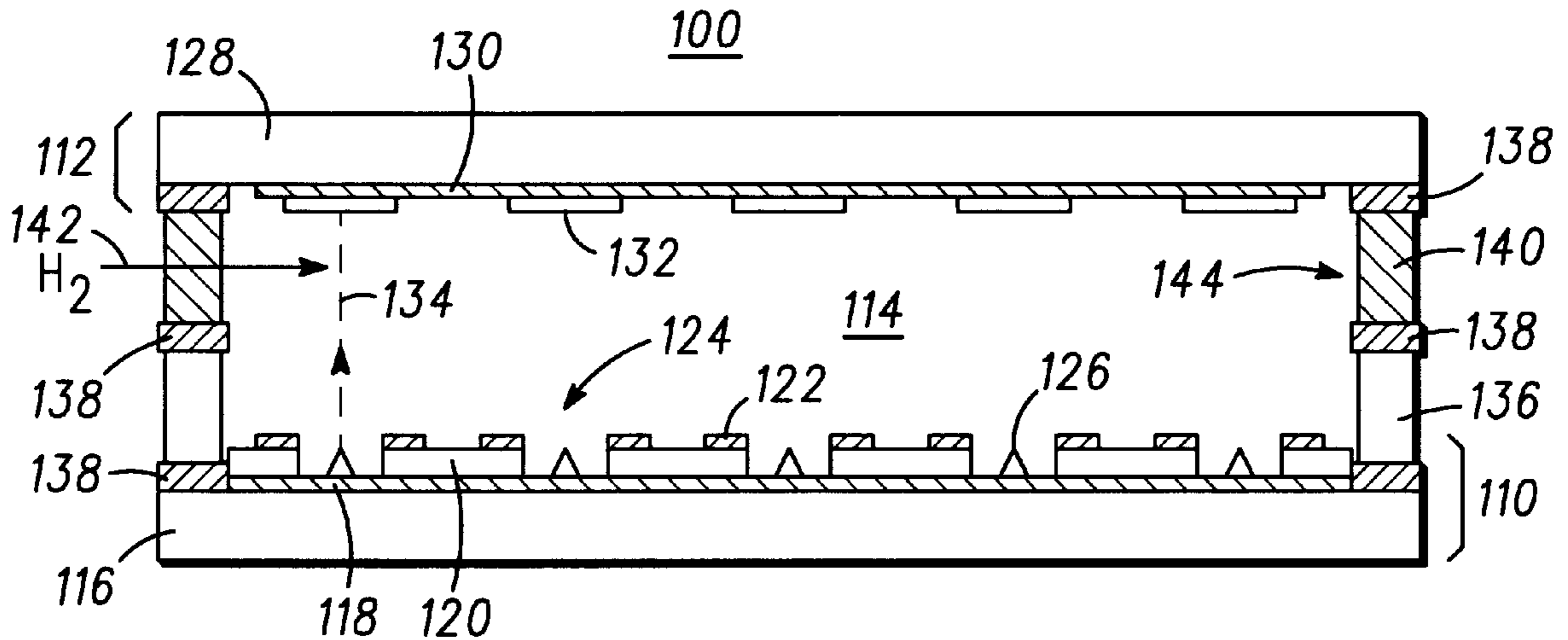


FIG. 1

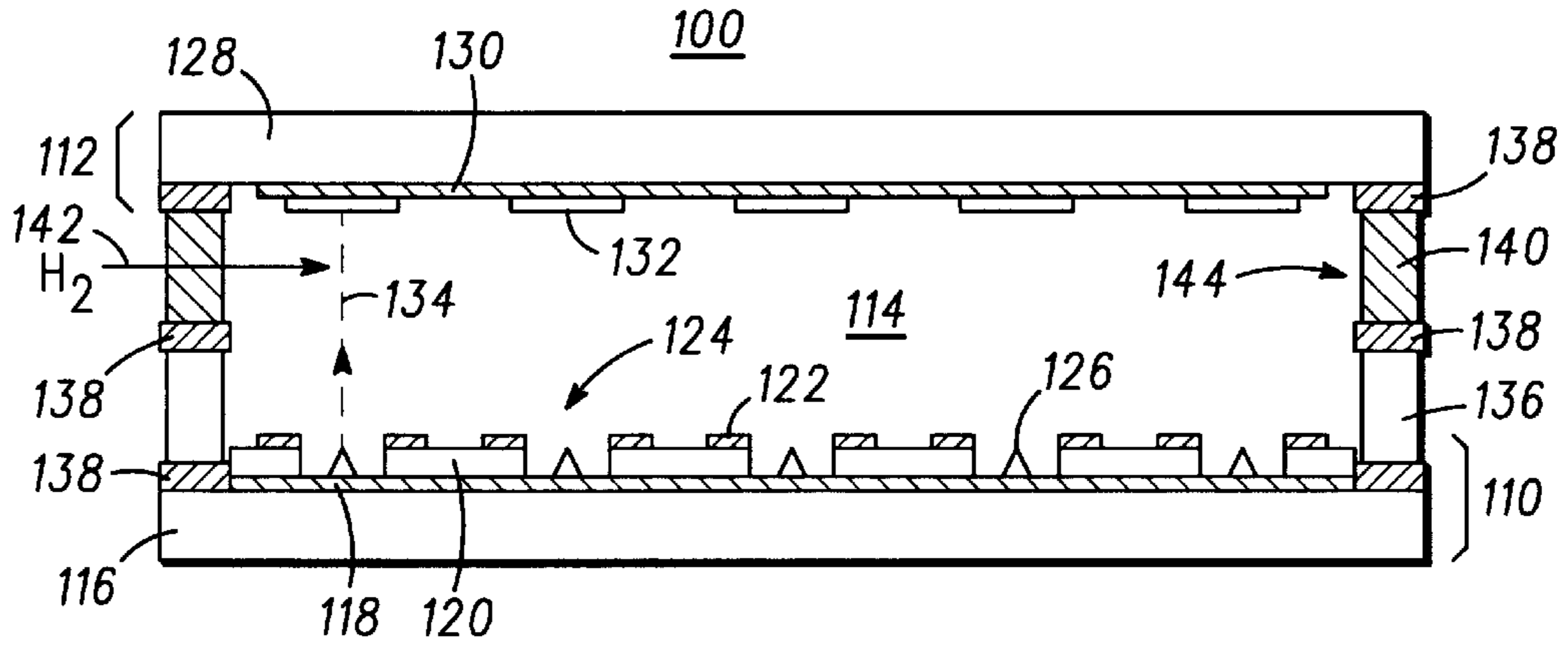


FIG. 2

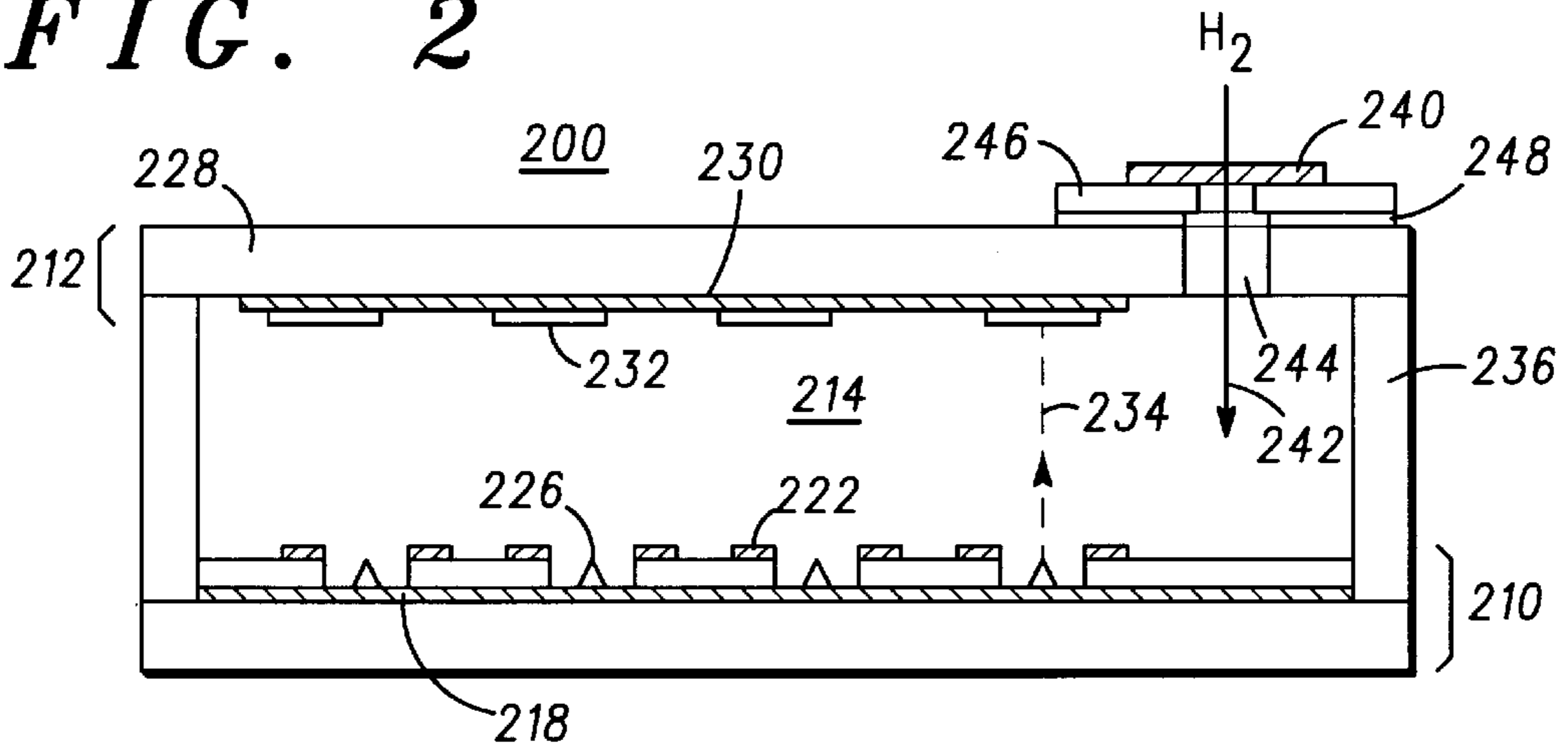


FIG. 4

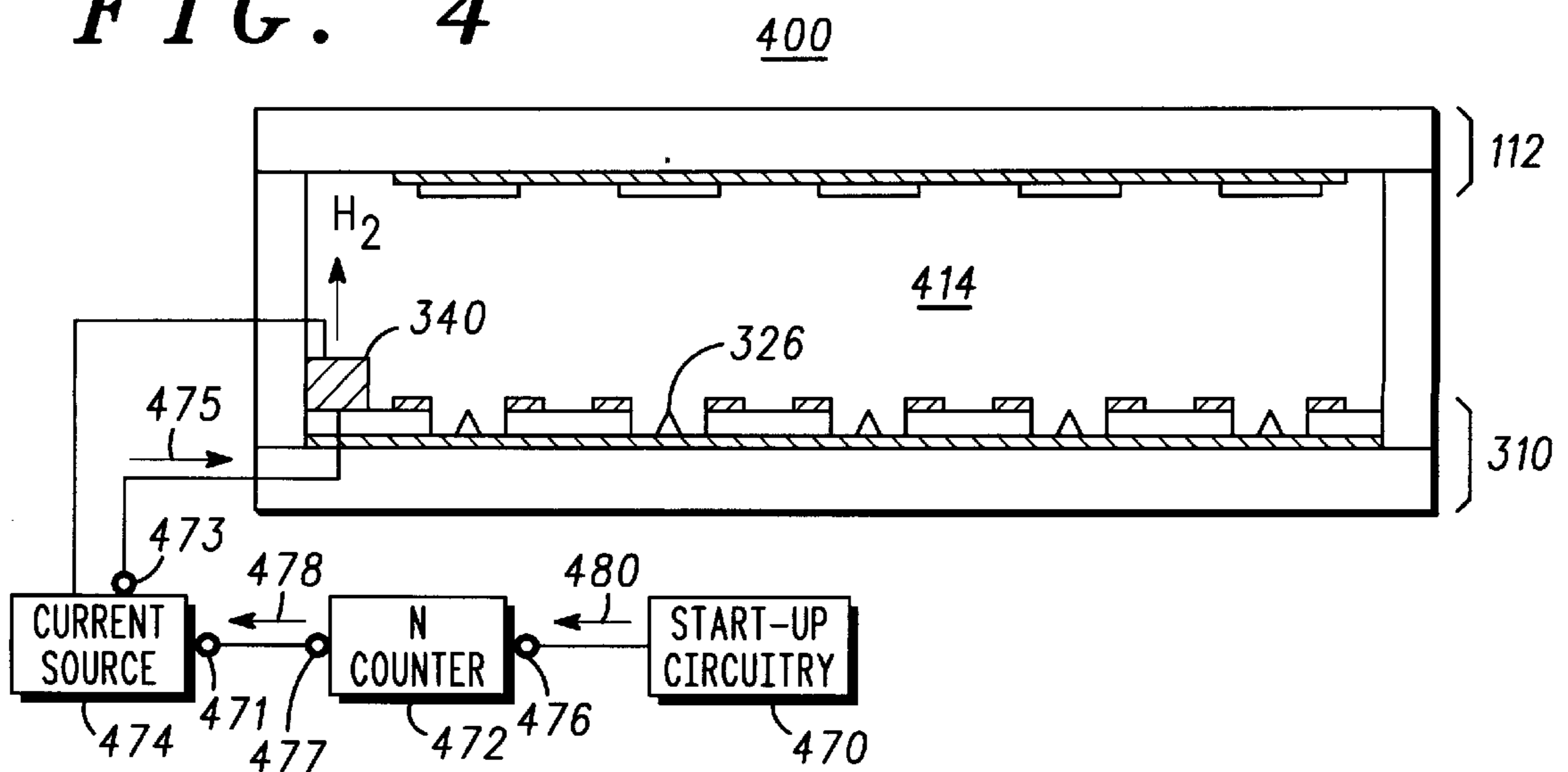
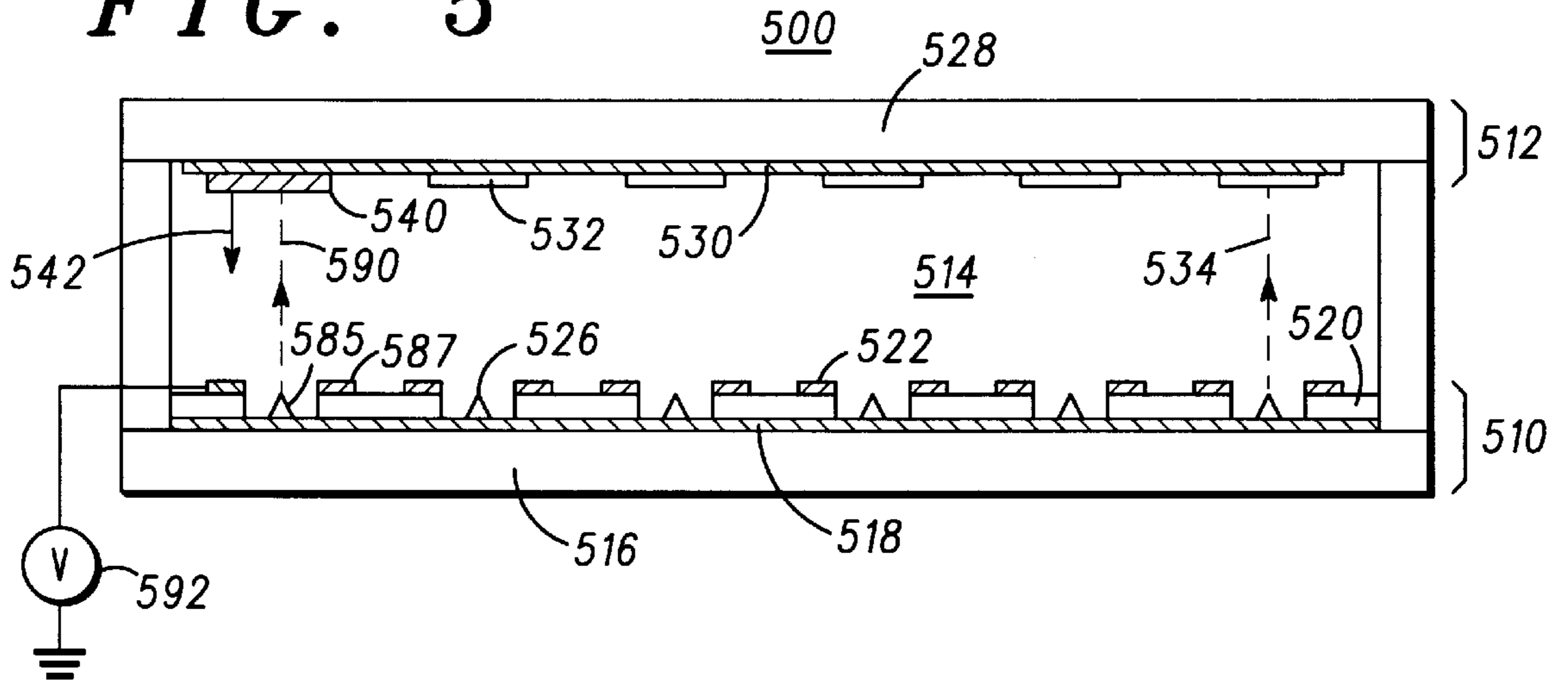


FIG. 5



METHOD FOR IN SITU CLEANING OF ELECTRON EMITTERS IN A FIELD EMISSION DEVICE

REFERENCE TO RELATED APPLICATION

Related subject matter is disclosed in a co-pending, commonly assigned patent application entitled "Field Emission Device Having Means for in Situ Feeding of Hydrogen", attorney docket number FD97060, filed on even date herewith.

FIELD OF THE INVENTION

The present invention pertains to the area of field emission devices and, more particularly, to methods for cleaning and conditioning electron emitters in a field emission device.

BACKGROUND OF THE INVENTION

A typical field emission device contains electron emitters, such as Spindt tips, which are made from an electron-emissive metal, such as molybdenum. These electron emitters are susceptible to surface contamination by oxygen-containing and carbon-containing species. The surface oxygen and carbon have deleterious effects on the electron emission properties of the electron emitters. In particular, the presence of oxygen and carbon at the emissive surface increases the surface work function of the electron emitters. That is, a bigger electric field is required to extract electrons therefrom due to the contamination. Surface contaminants also result in emission current instability and reduced device lifetime.

Metal field emission tips have been employed in field emission electron and ion microscopy, scanning tunneling microscopy, etc. It is known to remove surface contaminants from electron emitters in these microscopy systems by employing high temperature (greater than 2000°K) flashing. However, field emission arrays often include glass substrates upon which the electron emitters are formed. These glass substrates have temperature tolerances upwards of 700–800°K. Thus, high temperature cleaning procedures cannot be used for decontaminating field emission electron emitters formed on glass substrates.

Furthermore, the contamination of field emission electron emitters occurs throughout the life of the field emission device. Contaminant gaseous species are introduced into the vacuum of the field emission device by outgassing from surfaces, by electron-stimulated desorption from the phosphors and other surfaces that are exposed to field emitted electrons, by small leaks in the packaging elements, etc.

In order to maintain constant emission characteristics over the life of the device, it is desirable that emitter surface contaminants be removed throughout the life of the device. It is also desirable that this cleaning process be continuous over the life of the device or be performed periodically at a frequency that is sufficient to prevent appreciable deterioration of emission characteristics. However, field emission devices typically have no convenient means for introducing cleaning agents into the device subsequent to the vacuum sealing of the device package.

Accordingly, there exists a need for a method for in situ decontamination of electron emitters in field emission devices.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross-sectional view of a first embodiment of a field emission device useful for performing steps of a method in accordance with the invention;

FIG. 2 is a cross-sectional view of a second embodiment of a field emission device useful for performing steps of a method in accordance with the invention;

FIG. 3 is a cross-sectional view of a third embodiment of a field emission device useful for performing steps of a method in accordance with the invention and includes a block diagram of a configuration for controlling the rate of hydrogen evolution from a hydrogen source in accordance with the invention;

FIG. 4 is a cross-sectional view of a fourth embodiment of a field emission device useful for performing steps of a method in accordance with the invention and includes a block diagram of a configuration for controlling the rate of hydrogen evolution from a hydrogen source; and

FIG. 5 is a cross-sectional view of a fifth embodiment of a field emission device useful for performing steps of a method in accordance with the invention.

It will be appreciated that for simplicity and clarity of illustration, elements shown in the FIGURES have not necessarily been drawn to scale. For example, the dimensions of some of the elements are exaggerated relative to each other. Further, where considered appropriate, reference numerals have been repeated among the FIGURES to indicate corresponding elements.

DESCRIPTION

The invention is for a method for in situ cleaning of electron emitters in a field emission device. The method of the invention includes the steps of providing hydrogen gas within the device during the operational life of the device and, thereafter, causing the electron emitters of the field emission device to emit electrons. These electrons interact with the hydrogen gas to form hydrogen free radicals, which are useful for cleaning and conditioning the surfaces of the electron emitters. The decontaminated emissive surfaces provide stable emission current during the operational life of the device. The method of the invention further includes the step of providing within the field emission device hydrogen gas at a rate/frequency sufficient to maintain the surfaces of the electron emitters free of contaminants and thereby maintain stable electron emission over the life of the device.

The field emission devices described herein are directed to field emission display devices having triode configurations and employing Spindt tip electron emitters. However, the scope of the invention is not intended to be limited to display devices, to devices having a triode configuration, nor to devices having Spindt tip electron emitters. In general, the invention can be embodied in a vacuum device that employs field emission electron emitters, such as Spindt tips, edge emitters, wedge emitters, surface conduction emitters, and the like, which are made from a material that can be cleaned/decontaminated using hydrogen free-radicals. Also, the invention can be embodied in a field emission device having a diode configuration or a configuration having greater than three electrodes.

FIG. 1 is a cross-sectional view of a first embodiment of a field emission device (FED) 100 useful for performing steps of a method for in situ cleaning of a plurality of electron emitters 126 in accordance with the invention. FED 100 is an operational device. That is, FED 100 has the operational configuration that is intended for its functional life. FED 100 is evacuated, and the device package components are hermetically sealed. The method of the invention is useful for providing hydrogen gas within FED 100 at a time during the operational life of FED 100, subsequent to its evacuation and sealing. This allows for in situ cleaning of electron emitters 126.

FED 100 includes a cathode plate 110, which is spaced from an anode plate 112 to define an interspace region 114 therebetween. Cathode plate 110 includes a plurality of electron emitters 126. In general, during the operation of FED 100, electrons, indicated by a dashed line 134 in FIG. 1, are emitted by electron emitters 126 and are subsequently collected at anode plate 112.

Cathode plate 110 includes a substrate 116, which can be made from glass, silicon, or some other hard, dielectric material. Upon substrate 116 is disposed a plurality of cathodes 118, which are electrodes made from a conductor, such as molybdenum, aluminum, and the like. A dielectric layer 120 is disposed on cathodes 118 and defines a plurality of emitter wells 124. Electron emitters 126 are disposed one each in emitter wells 124. In the embodiment of FIG. 1, electron emitters 126 include Spindt tips. Electron emitters 126 are made from a field emissive material. Exemplary field emissive materials include molybdenum, niobium, hafnium, tungsten, iridium, silicon, diamond-like carbon, and the like. In general, the field emissive material can be induced to emit electrons by the application of an electric field of appropriate strength. Also, the field emissive material can be conditioned/cleaned using hydrogen free radicals, which include atomic hydrogen and hydrogen ions.

A plurality of gate extraction electrodes 122 is configured upon dielectric layer 120 for selectively addressing electron emitters 126. Gate extraction electrodes 122 are made from a conductive material, such as molybdenum, aluminum, and the like. Methods for fabricating cathode plate 110 are known to one skilled in the art.

Anode plate 112 includes a transparent substrate 128 made from a solid, transparent material, such as a glass. An anode 130 is formed on transparent substrate 128. Anode 130 is made from a transparent, conductive material, such as indium tin oxide. Anode plate 112 further includes a plurality of phosphors 132, which are made from a cathodoluminescent material.

Between cathode plate 110 and anode plate 112, at their peripheries, is disposed a frame 136, which provides stand-off therebetween. Frame 136 can be made from a glass and is affixed to cathode plate 110 with a sealant 138. Sealant 138 can be a frit sealant, indium metal, tin, indium tin alloys, other low melting point metals, and the like. Cathode plate 110, anode plate 112, and frame 136 define a device package.

A hydrogen-selective membrane 140 is disposed within a hole 144 defined by frame 136 and anode plate 112. Hydrogen-selective membrane 140 is made from a refractory metal, such as palladium, nickel, a palladium alloy, a nickel alloy, and the like, which is selectively permeable with respect to hydrogen. Preferably, hydrogen-selective membrane 140 is made from palladium. Hydrogen-selective membrane 140 has a thickness, in the direction of hydrogen diffusion, within a range of 50–500 micrometers. Under the appropriate conditions of temperature and pressure, hydrogen gas is capable of selectively diffusing through hydrogen-selective membrane 140.

FED 100 can be fabricated by first silk-screening sealant 138 onto transparent substrate 128 at the periphery thereof. Then, hydrogen-selective membrane 140 is disposed on sealant 138. Refractory metal membranes, having thicknesses greater than about 10 micrometers, are available commercially. Such a refractory metal membrane can be cut into a suitable shape to form hydrogen-selective membrane 140. The structure is then heated to affix the refractory metal to sealant 138.

Anode plate 112, having hydrogen-selective membrane 140 formed thereon, is assembled with cathode plate 110, having frame 136 affixed thereto, in a vacuum environment, so that a vacuum is realized within interspace region 114. As illustrated in FIG. 1, hydrogen-selective membrane 140 is thus disposed in communication with interspace region 114. That is, hydrogen gas, which is indicated by an arrow 142 in FIG. 1, that diffuses through hydrogen-selective membrane 140 can subsequently travel into interspace region 114.

Subsequent to the steps of sealing the elements of FED 100 and establishing a vacuum environment therein, the following steps are used to achieve in situ feeding of hydrogen gas into interspace region 114 and in situ cleaning of electron emitters 126, in accordance with the invention. First, FED 100 is placed in an oven having a hydrogen atmosphere. The hydrogen atmosphere within the oven has a hydrogen partial pressure within a range of milli-Torr to several atmospheres. Then, the temperature within the oven is elevated to within a range of about 273–450°K. In general, the temperature and partial pressure of hydrogen within the hydrogen atmosphere are selected to promote diffusion of hydrogen gas through hydrogen-selective membrane 140. The hydrogen gas can be controllably provided by manipulating the temperature and the hydrogen pressure external to FED 100 during the diffusion step.

The diffusion of hydrogen into interspace region 114 is performed for a period of time sufficient to provide within interspace region 114 a partial pressure of hydrogen useful for cleaning electron emitters 126. In accordance with the invention, a partial pressure of hydrogen is achieved within FED 100 that is preferably greater than 10^{-8} Torr, most preferably within a range of 10^{-8} – 10^{-5} Torr.

The hydrogen content can be determined by measuring the total pressure within FED 100 prior to the addition of hydrogen and thereafter measuring the total pressure within FED 100 after the addition of hydrogen. If these two measurements are taken at the same temperature, the final hydrogen partial pressure can be derived therefrom by, for example, using the ideal gas law.

In general, clean electron emitters 126 ameliorate the fluctuations in the emission current for a given set of conditions, including operating voltages and temperature. Thus, the level of contamination of electron emitters 126 can be deduced from measured fluctuations in the emission current. Contamination of electron emitters 126 is also reflected by a reduction in the emission current for a given set of emission parameters. In accordance with the invention, a partial pressure of hydrogen is established within interspace region 114 that provides stabilized, constant emission current having fluctuations within a tolerable range. For example, it may be desirable to maintain current fluctuations of less than 0.5% per hour for a given set of conditions.

Subsequent to the step of providing a partial pressure of hydrogen gas within interspace region 114 useful for cleaning electron emitters 126, electron emitters 126 are activated to emit electrons. Electron emission is realized by applying the appropriate potentials to cathodes 118 and gate extraction electrodes 122, as is known to one skilled in the art. The emitted electrons are then attracted toward anode 130 by applying thereto an appropriate potential. As they travel across interspace region 114, the emitted electrons dissociate and ionize the hydrogen molecules present therein, thereby forming hydrogen free radicals within interspace region 114.

The hydrogen free-radicals, which include hydrogen ions and energetic neutral hydrogen atoms, react with the sur-

faces of electron emitters **126**, which include surface contaminants, to form volatile hydrides. Exemplary volatile hydrides that may be produced include: H_2O , MoH_x^+ ($x=1-3$), $MoOH^+$, OH^+ , OH , H^+ , CH_x^+ , ($x=1-4$), and the like. These volatile hydrides are then removed from interspace region **114** by gettering material (not shown) present within FED **100**.

It is desired to be understood that the cleaning process is not limited to the removal of contaminants in the form of hydrides alone. The hydrogen free radicals are also capable of catalyzing surface chemical reactions, which produce volatile products that do not include hydrides and which effectively remove surface contaminants.

In accordance with the invention, the steps for cleaning and conditioning electron emitters **126** can be performed shortly after sealing of the device package to remove surface contaminants, native oxides, and process residues. These steps can also be performed after a period of use of FED **100**, thereby reconditioning electron emitters **126** and removing surface contaminants accumulated during the operation of FED **100**. This cleaning procedure is preferably performed periodically over the life of FED **100**, at a frequency sufficient to maintain clean electron emitters **126**. In this manner, stable, constant electron emission is realized over the life of FED **100**.

In general, the means for in situ feeding of hydrogen is disposed in communication with the interspace region of the device package. In the embodiment having a hydrogen-selective membrane, the hydrogen-selective membrane is configured in registration with a hole/gap defined by the device package. Under appropriate conditions of pressure and temperature, this configuration allows hydrogen gas to diffuse from a hydrogen atmosphere external to the field emission device, through the hydrogen-selective membrane, and into the interior of the field emission device.

FIG. **2** is a cross-sectional view of a second embodiment of a field emission device (FED) **200** useful for performing steps of a method in accordance with the invention. FED **200** includes a hydrogen-selective membrane **240**, which is disposed in registration with a hole **244** defined by the device package. Hole **244** is defined by a transparent substrate **228** of an anode plate **212**. Transparent substrate **228** is made from a hard, transparent material, such as a glass, and has affixed thereto an anode **230** and a plurality of phosphors **232**. Hydrogen-selective membrane **240** overlies hole **244**. Hydrogen-selective membrane **240** includes a membrane made from a refractory metal such as palladium, nickel, and the like, which is selectively permeable to hydrogen. The thickness of hydrogen-selective membrane is preferably within a range of 50–500 micrometers.

FED **200** is fabricated by first making a cathode plate **210**, in a manner similar to that described with reference to FIG. **1**. Cathode plate **210** includes a plurality of cathodes **218**, a plurality of electron emitters **226**, and a plurality of gate extraction electrodes **222**. A frame **236** is attached to the periphery of cathode plate **210** by using a frit sealant (not shown). Anode plate **212** is attached to frame **236** to define an interspace region **214**. The step of attaching anode plate **212** can be performed in air because, subsequent to the sealing process, interspace region **214** can be evacuated through hole **244** using a vacuum pump, as is known to one skilled in the art.

Hydrogen-selective membrane **240** is affixed to anode plate **212** by first providing a ring **246** made from an alloy having thermal expansion characteristics that match those of transparent substrate **228**. Hydrogen-selective membrane

240 is brazed to ring **246**, so that it covers the hole defined by ring **246**. Then the hole defined by ring **246** is positioned in registration with hole **244** of transparent substrate **228**. Ring **246** is attached to transparent substrate **228** using a frit sealant **248**. The step of attaching ring **246**, having hydrogen-selective membrane **240** affixed thereto, to transparent substrate **228** is performed subsequent to the evacuation of the device package.

Subsequent to the step of attaching hydrogen-selective membrane **240** to the device package, a hydrogen partial pressure is established within FED **200**, in a manner similar to that described with reference to FIG. **1**. Under appropriate conditions of temperature and pressure, hydrogen gas, which is indicated by an arrow **242** in FIG. **2**, is diffused through hydrogen-selective membrane **240** and travels into interspace region **214**. Within interspace region **214**, the hydrogen gas is converted into hydrogen free radicals by electrons, which are indicated by a dashed line **234** in FIG. **2**, that are emitted by electron emitters **226**.

FIG. **3** is a cross-sectional view of a third embodiment of a field emission device (FED) **300** useful for performing steps of a method in accordance with the invention, and includes a block diagram of means for controlling the rate of hydrogen evolution from a hydrogen source **340**. Similar to FED **100** and FED **200** of FIGS. **1** and **2**, respectively, FED **300** is an operational device. That is, FED **300** has the operational configuration that is intended for its functional life. FED **300** is evacuated, and the device package components are hermetically sealed. The method of the invention is useful for providing hydrogen gas within FED **300** at a time during the operational life of FED **300**, subsequent to its evacuation and sealing. This allows for in situ cleaning of a plurality of electron emitters **326**.

In accordance with the invention, a method for in situ cleaning of electron emitters **326** includes the steps of providing hydrogen source **340** within FED **300**, releasing hydrogen gas from hydrogen source **340**, and, thereafter, forming hydrogen free radicals from the hydrogen gas. The components of the block diagram of FIG. **3** are useful for controllably releasing the hydrogen gas from hydrogen source **340**. In the embodiment of FIG. **3**, the step of controllably releasing hydrogen gas from hydrogen source **340** includes the step of releasing hydrogen gas from hydrogen source **340** in response to a drop below a predetermined value of a test emission current **358** measured at a test electron emitter **359** in FED **300**.

FED **300** has a cathode plate **310** and an anode plate **312**, which define an interspace region **314**. FED **300** further includes hydrogen source **340**, which is disposed within interspace region **314**. Hydrogen source **340** includes a solid member made from a refractory metal, such as palladium, nickel, a palladium alloy, a nickel alloy, and the like. Preferably, hydrogen source **340** is made from palladium. Hydrogen source **340** is secured to one of the surfaces defining interspace region **314** by a convenient method, such as by using a frit sealant or mechanical means.

Hydrogen source **340** contains hydrogen. In accordance with the invention, hydrogen is provided within hydrogen source **340** by first placing the metallic member in an oven having a hydrogen atmosphere. The temperature in the oven is elevated to induce the diffusion of hydrogen gas into the metallic member. After a sufficient amount of hydrogen has been diffused into the metallic member, the metallic member is cooled, thereby entrapping the hydrogen contained therein.

In accordance with the invention, electron emitters **326** are cleaned and conditioned by first controllably releasing

hydrogen gas, which is indicated by an arrow 342 in FIG. 3, from hydrogen source 340. The rate/frequency of hydrogen evolution from hydrogen source 340 is controlled so as to provide within interspace region 314 a partial pressure of hydrogen that is useful for maintaining a stable emission current. A dashed line 334 in FIG. 3 indicates the emission current.

The step of releasing hydrogen gas from hydrogen source 340 includes the step of heating hydrogen source 340. Hydrogen source 340 can be heated by passing a current directly through hydrogen source 340. Alternatively, hydrogen source 340 can be heated by providing a heating element, such as a resistive wire, and providing thermal contact between hydrogen source 340 and the heating element. Subsequent to the step of heating hydrogen source 340, hydrogen free radicals are produced from the hydrogen gas, in the manner described with reference to FIGS. 1 and 2. Hydrogen source 340 can also be heated by using an infrared laser.

Illustrated in FIG. 3 is a block diagram of a control system useful for controlling the rate of hydrogen evolution from hydrogen source 340 in accordance with the method of the invention. The control system includes a switching circuit 354, a controller 356, a temperature measurement device 366, and a current measurement device 362.

Controller 356 controls test emission current 358 that is emitted by test electron emitter 359. The characteristics of test emission current 358 are representative of the characteristics of the emission currents from the remainder of electron emitters 326. Controller 356 controls test emission current 358 by manipulating the rate of hydrogen evolution from hydrogen source 340 in response to a first signal 364 from current measurement device 362 and a second signal 368 from temperature measurement device 366.

A current measurement electrode 360 is configured on anode plate 312 to receive test emission current 358. Current measurement device 362 is connected to current measurement electrode 360 for measuring test emission current 358. Current measurement device 362 transmits first signal 364, which is related to test emission current 358, to a first input terminal 361 of controller 356.

Temperature measurement device 366 measures a temperature within interspace region 314 and transmits second signal 368, which is related to the temperature, to a second input terminal 363 of controller 356. The value of the emission current is dependent, in part, upon temperature. Controller 356 corrects for this temperature dependence when determining the status of the emission current. When the corrected value of the emission current drops below a predetermined level, the controller transmits a control signal 357 to a first input terminal 353 of switching circuit 354.

Switching circuit 354 is responsive to control signal 357. Switching circuit 354 has an output that is connected to hydrogen source 340 for transmitting an activation current 350 thereto. In general, switching circuit 354 transmits activation current 350 to hydrogen source 340 when the corrected emission current drops below a predetermined value due to surface contamination of electron emitters 326. In the embodiment of FIG. 3, a voltage source 352 is connected to a second input terminal 351 of switching circuit 354. Voltage source 352 can be included in the power supply of FED 300.

Due to the heating of hydrogen source 340, the temperature within FED 300 may increase. It is desired to maintain the temperature within FED 300 below that which results in an excessive, catastrophic emission current at electron emit-

ters 326. Controller 356 is designed to cease heating hydrogen source 340 when the temperature measured by temperature measurement device 366 reaches an upper limit. In this manner, the emission current is prevented from attaining a catastrophic level due to overheating within FED 300 caused by the heating of hydrogen source 340.

FIG. 4 is a cross-sectional view of a fourth embodiment of a field emission device (FED) 400 useful for performing steps of a method in accordance with the invention, and includes a block diagram of means for controlling the rate of hydrogen evolution from hydrogen source 340. In the method for in situ cleaning of electron emitters 326 of FED 400, the step of controllably releasing hydrogen gas from hydrogen source 340 includes the step of releasing hydrogen gas in response to the activation of FED 400. In this manner, the rate of cleaning of electron emitters 326 is responsive to the extent of use of FED 400.

FED 400 includes anode plate 112 and cathode plate 310, which define an interspace region 414. In the embodiment of FIG. 4, the system for controlling the rate of hydrogen evolution from hydrogen source 340 includes a current source 474 and an N-counter circuit 472.

FED 400 has a start-up circuit 470, which initially activates the device. Start-up circuit 470 is coupled to cathode plate 310 and anode plate 112 (connections not shown) and provides the proper operating voltage for powering FED 400. When start-up circuit 470 is activated, it transmits a start-up signal 480 to an input terminal 476 of N-counter circuit 472. Start-up signal 480 triggers a counter. When the counter reaches N, N-counter circuit 472 transmits from an output terminal 477 an activation signal 478. Activation signal 478 is received at an input terminal 471 of current source 474.

Current source 474 has an output terminal 473 that is connected to hydrogen source 340. Upon receipt of activation signal 478, current source 474 transmits an activation current 475 to hydrogen source 340, resulting in evolution of hydrogen gas from hydrogen source 340.

The amount of current sent to hydrogen source 340 each time N-counter reaches N and the value of N depend upon factors such as the size of FED 400 and the anticipated extent of contamination during a given period of use of FED 400. The latter factor depends in part upon the nature of the materials present within FED 400. For example, different materials may generate contaminants at different rates.

In accordance with the invention, the step of controllably releasing hydrogen gas from a hydrogen source can include the step of periodically releasing hydrogen gas from the hydrogen source. A field emission device useful for performing periodic hydrogen emissions has a configuration similar to that depicted in FIG. 4 and includes a control system having a timer circuit. In this embodiment, a current source is connected to the hydrogen source; however, the timer circuit is substituted for the N-counter circuit. The timer circuit generates a periodic activation signal, which is transmitted to the current source. In this manner, a predetermined amount of current can be periodically transmitted to the hydrogen source at predetermined intervals. For example, hydrogen evolution can be provided once per month using this configuration.

The step of maintaining within the field emission device a partial pressure of hydrogen gas sufficient to maintain stable electron emission can also include the step of maintaining within the field emission device a partial pressure of hydrogen greater than 10^{-8} Torr, preferably within a range of 10^{-8} – 10^{-5} Torr. A field emission device useful for perform-

ing this step includes a feedback control system, similar to that of FIG. 3, for controlling the hydrogen partial pressure. For example, this feedback control system can include a device for measuring the total pressure within the device. A change in the total pressure can be attributable to a change in the partial pressure of hydrogen. The pressure measurement device transmits a signal, which is related to total pressure, to a controller. When the pressure drops below a predetermined value, the controller transmits a control signal to a switch or current source, to generate an activation current. The activation current is transmitted to the hydrogen source to cause hydrogen evolution therefrom.

FIG. 5 is a cross-sectional view of a fifth embodiment of a field emission device (FED) 500 useful for performing steps of a method in accordance with the invention. The introduction of hydrogen, which is indicated by an arrow 542, into an interspace region 514 of FED 500 is realized by an electron-stimulated hydrogen desorption process. Specifically, the step of releasing hydrogen gas from a hydrogen source 540 includes the step of impinging electrons, which are indicated by a dashed line 590, onto hydrogen source 540. The rate of hydrogen evolution depends upon the density and energy of the impinging electron beam, and no thermal heating of hydrogen source 540 is required.

In the embodiment of FIG. 5, an activation electron emitter 585 provides the impinging electron beam. Hydrogen source 540 opposes activation electron emitter 585. Hydrogen source 540 is made in the manner described with reference to hydrogen source 340 of FIGS. 3 and 4. A cathode plate 510 includes activation electron emitter 585, which is one of a plurality of electron emitters 526 disposed within emitter wells defined by a dielectric layer 520. Electron emitters 526 are connected to a plurality of cathodes 518, which are disposed on a substrate 516.

An activation gate extraction electrode 587 is disposed proximate to activation electron emitter 585 and is coupled to a voltage source 592. Activation gate extraction electrode 587 is controlled independently from a plurality of gate extraction electrodes 522, which are used to selectively address those of electron emitters 526 that oppose a plurality of phosphors 532.

Selectively addressing activation electron emitter 585 controllably provides the hydrogen gas. Voltage source 592 is used to selectively apply an extraction voltage at activation gate extraction electrode 587. When hydrogen evolution from hydrogen source 540 is desired, voltage source 592 is used to apply the extraction voltage to activation gate extraction electrode 587, thereby realizing electron emission from activation electron emitter 585. When no hydrogen evolution from hydrogen source 540 is desired, voltage source 592 is used to apply a voltage that does not result in electron emission from activation electron emitter 585. The output voltage of voltage source 592 can be manipulated using one of a number of useful control methods, such as those described with reference to FIGS. 3 and 4.

An electron-attracting voltage is provided at hydrogen source 540 by a voltage source (not shown), so that the electrons from activation electron emitter 585 are attracted to and collected at hydrogen source 540. In the embodiment of FIG. 5, hydrogen source 540 is disposed on an anode plate 512. Anode plate 512 includes a transparent substrate 528, upon which is formed an anode 530. Hydrogen source 540 is connected to anode 530, to which the electron-attracting voltage is applied. Phosphors 532 are also configured on anode 530. The electrons collected at hydrogen source 540

stimulate hydrogen evolution therefrom. The hydrogen thus evolved is then ionized by electrons within interspace region 514, including the electrons, which are generally indicated by a dashed line 534, directed toward phosphors 532.

In an alternative embodiment, the hydrogen source is not coupled to the anode. Rather, the hydrogen source is coupled to an independent voltage source, so that the voltage at the hydrogen source can be manipulated independently from the voltage at the phosphors. In this particular embodiment, the electrons for use for hydrogen evolution can be provided by any of the electron emitters within the device. The emitted electrons are directed toward the hydrogen source by selectively biasing it to attract the electrons. For example, subsequent to the sealing and evacuation of the device, some or all of the electron emitters are caused to emit electrons. Simultaneously, a positive, attracting voltage is selectively applied to the hydrogen source. After the decontamination steps are completed, the positive, attracting voltage is removed from the hydrogen source. Any subsequently emitted electrons can be directed toward the phosphors by selectively applying a positive, attracting voltage to the phosphors.

In summary, the invention is for a method for in situ cleaning of electron emitters in a field emission device. The method of the invention includes steps for controllably providing hydrogen gas within the field emission device and, thereafter, forming hydrogen free radicals from the hydrogen gas. The hydrogen free radicals are useful for cleaning the electron emitters. The steps of the method of the invention can be performed at any time subsequent to the vacuum sealing of the device package. Further, the hydrogen gas is controllably introduced at a rate/frequency sufficient to remove surface contaminants and maintain clean electron emitters, thereby realizing stable electron emission over the life of the device.

While we have shown and described specific embodiments of the present invention, further modifications and improvements will occur to those skilled in the art. We desire it to be understood, therefore, that this invention is not limited to the particular forms shown, and we intend in the appended claims to cover all modifications that do not depart from the spirit and scope of this invention.

We claim:

1. A method for in situ cleaning of electron emitters in a field emission device comprising the steps of:

introducing hydrogen gas into the field emission device at a time subsequent to sealing of the field emission device; and

thereafter, forming hydrogen free radicals from the hydrogen gas.

2. The method for in situ cleaning of electron emitters as claimed in claim 1, wherein the step of introducing hydrogen gas into the field emission device includes the step of controllably introducing hydrogen gas within the field emission device.

3. The method for in situ cleaning of electron emitters as claimed in claim 2, wherein the step of controllably introducing hydrogen gas into the field emission device includes the step of periodically introducing hydrogen gas within the field emission device.

4. The method for in situ cleaning of electron emitters as claimed in claim 1, wherein the step of forming hydrogen free radicals from the hydrogen gas includes the step of emitting electrons from the electron emitters.

5. The method for in situ cleaning of electron emitters as claimed in claim 1, wherein the step of introducing hydrogen

gas into the field emission device includes the step of diffusing hydrogen gas through a hydrogen-selective membrane.

6. The method for in situ cleaning of electron emitters as claimed in claim 5, wherein the step of diffusing hydrogen gas through a hydrogen-selective membrane includes the step of diffusing hydrogen gas through a hydrogen-selective membrane disposed in registration with a hole defined by the device package.

7. A method for in situ cleaning of electron emitters in a field emission device having an evacuated interspace region, the method comprising the steps of:

providing a hydrogen source within the evacuated interspace region of the field emission device;

releasing hydrogen gas from the hydrogen source; and

thereafter, forming hydrogen free radicals from the hydrogen gas.

8. The method for in situ cleaning of electron emitters as claimed in claim 7, wherein the step of providing a hydrogen source includes the steps of providing a member made from a refractory metal, heating the member in a hydrogen atmosphere, and thereafter cooling the member, thereby entrapping hydrogen within the member.

9. The method for in situ cleaning of electron emitters as claimed in claim 8, wherein the step of providing a member made from a refractory metal includes the step of providing a member made from palladium.

10. The method for in situ cleaning of electron emitters as claimed in claim 7, wherein the step of releasing hydrogen gas from the hydrogen source includes the step of impinging electrons onto the hydrogen source.

11. The method for in situ cleaning of electron emitters as claimed in claim 10, wherein the step of impinging electrons onto the hydrogen source includes the step of impinging onto the hydrogen source electrons emitted by at least one of the electron emitters.

12. The method for in situ cleaning of electron emitters as claimed in claim 7, wherein the step of releasing hydrogen gas from the hydrogen source includes the step of heating the hydrogen source.

13. The method for in situ cleaning of electron emitters as claimed in claim 7, wherein the step of forming hydrogen free radicals from the hydrogen gas includes the step of emitting electrons from the electron emitters.

14. The method for in situ cleaning of electron emitters as claimed in claim 7, wherein the step of releasing hydrogen

gas from the hydrogen source includes the step of controllably releasing hydrogen gas from the hydrogen source.

15. The method for in situ cleaning of electron emitters as claimed in claim 14, wherein the step of controllably releasing hydrogen gas from the hydrogen source includes the step of releasing hydrogen gas from the hydrogen source in response to activation of the field emission device.

16. The method for in situ cleaning of electron emitters as claimed in claim 14, wherein the step of controllably releasing hydrogen gas from the hydrogen source includes the step of periodically releasing hydrogen gas from the hydrogen source.

17. The method for in situ cleaning of electron emitters as claimed in claim 14, wherein the step of controllably releasing hydrogen gas from the hydrogen source includes the step of releasing hydrogen gas from the hydrogen source in response to the drop below a predetermined value of a test emission current measured at a test electron emitter in the field emission device.

18. The method for in situ cleaning of electron emitters as claimed in claim 14, wherein the step of controllably releasing hydrogen gas from the hydrogen source includes the step of releasing hydrogen gas from the hydrogen source at a rate sufficient to clean the electron emitters and thereby maintain stable electron emission for a given set of conditions within the field emission device.

19. A method for in situ cleaning of electron emitters in a field emission device comprising the steps of:

sealing the field emission device; and

thereafter, adjusting a partial pressure of hydrogen gas within the field emission device in a manner sufficient to maintain stable electron emission having fluctuations within a tolerable range.

20. The method for in situ cleaning of electron emitters as claimed in claim 19, wherein the step of adjusting a partial pressure of hydrogen gas includes the step of maintaining within the field emission device a partial pressure of hydrogen greater than 10^{-8} Torr.

21. The method for in situ cleaning of electron emitters as claimed in claim 20, wherein the step of adjusting a partial pressure of hydrogen gas includes the step of maintaining within the field emission device a partial pressure of hydrogen within a range of 10^{-8} to 10^{-5} Torr.

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